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Time Domain Network Analysis using the Multiline TRL Calibration

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Abstract–**We apply the multiline TRL (through-reflect-line) method to the calibration of a time domain network analyzer (TDNA). The calibration removes the effects of cables and connectors, nonideal source and sampler responses, source and sampler mismatch, and frequency-dependent characteristic impedance of the transmission lines. Multiline TRL is especially well suited to TDNA and provides not only a complete calibration but also a full characterization of the transmission lines, information useful in the study of interconnections**.

I. Introduction

A time domain network analyzer (TDNA) measures frequency-dependent network parameters using a transient source, typically in a time-domain reflection/transmission (TDR/TDT) configuration. TDNA (also an abbreviation for "time domain network analysis") offers the potential for low-cost network analysis at frequencies up to several hundred gigahertz [1,2]. However, like a frequency domain network analyzer (FDNA), a TDNA requires calibration to remove the effects of cables and connectors, nonideal source and sampler response, and source and sampler mismatch. Until recently, only partial error correction methods have been used to improve the quality of measured TDNA data.

In the past few years, more complete calibration techniques, similar to those developed for use with a conventional frequency domain network analyzer (FDNA), have been applied to TDNAs [3,4,5]. The methods of [1-4] are based on lumped-element standards, which are inherently inaccurate at high frequencies. While the accuracy may be sufficient in some cases, critical and broadband applications demand an alternative procedure.

The conventional TRL (through-reflect-line) calibration method, as applied in [5], uses transmission lines as fundamental calibration standards and thereby obviates the need for characterized transfer standards. However, it is limited in bandwidth. It also fails to account for the frequency-dependent characteristic impedance of the transmission lines.

The multiline TRL method [6] provides an accurate and well-characterized calibration that is suitable as a benchmark reference [7]. The multiline version permits calibration over a wide frequency band, necessary for an accurate calibrated time domain representation, and uses redundancy for the suppression of random error. The calibration method applied here also properly accounts for the frequency-dependent characteristic impedance Z_0 of the transmission lines, using the technique of [8]. Since this method provides not only a complete calibration but also a full characterization of the transmission lines, it is useful in the study of packaging interconnections [9].

In an earlier conference presentation [10], we discussed the application of the multiline TRL method to TDNA calibration. Here we report an improved calibration resulting from control of and correction for drift in the time base. TDNA is particularly susceptible to this error because slight variations in the time of the incident step lead to large inaccuracies at all frequencies. While internal TDR/TDT calibration methods [11] can best compensate for these errors, we consider here only an external method of drift correction. We illus-

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trate the results by comparing TDNA to a conventional frequency-domain network analyzer (FDNA). The agreement is excellent over the rated system bandwidth for both transmission line parameters and device impedances.

II. Error Model

The validity of the calibration technique depends on the validity of its assumed model. The model assumed by [4] is insufficient, without additional assumptions, for the application of TRL or similar methods. Reference [3] argues for a more general model in which the unknown is embedded in two two-port "error boxes." Such a model is amenable to modern vector network analyzer calibration methods. However, [5] and a followup paper [12] both demand the use of isolating air lines and time domain windowing (gating) to remove multiple reflections and separate forward and backward traveling waves. In [12], this is justified on the grounds that the switch mismatch differs depending on whether it is in the on or off state. Such an argument contradicts the general model of [3]. However, the argument is inapplicable to the many instruments (including ours and those of [5] and [12]) in which the TDR/TDT step is generated by a switch opening into the off state. Since the opposite port switch remains in the off state, all data collection takes place with all switches off. Therefore, the impedance in the on state is irrelevant.

Based on this analysis, we have assumed the applicability of the "error box" model and proceeded with the multiline TRL calibration without isolating air lines; instead, our sampling heads were mounted as close as possible to our probes. This model relies on the repeatability of the switches, which we expect to introduce negligible error.

III. Correction of Time Base Drift

Digital equivalent-time sampling oscilloscopes may suffer from time base irregularities that can seriously degrade TDNA performance. Figure 1 illustrates a typical problem–a slow drift in the time base offset. The figure shows the arrival of the incident step at the receiver during the measurement of several standards. Ideally, the waveforms should be identical, since this waveform portion represents the signal before the illumination of the standards. In fact, we can see a slight offset in the time axis due to a drift occurring between measurements. Offsets of this order lead to large frequency-domain phase errors in the microwave band.

For reflections, we can externally shift the acquired waveforms to largely eliminate these offsets. In our case, we performed the shift in the time domain after using the average offset between 0.01 and 0.12 V. However, for transmitted waveforms, we have no comparable early-time signal to use as a reference. Therefore, we applied the same offset correction to the transmitted signal as we did to the reflected signal using the corresponding source; that is, we shifted our raw S_{21} by the same amount as S_{11}. This correction is based on the presumption that the time base shift occurs in the source, rather than in the receiver; otherwise, it would be more appropriate to shift S_{12} by the same amount as S_{11}. This same presumption, which is consistent with the instrument's electronic design, is used in the time base correction algorithm of [11] and in the TDNA drift correction of [5], which appears similar to the correction performed here.

This correction is effective only for drifts which occur on a time scale slower than that of the acquisition of data for a single standard using a single source. In our case, this is at least plausible, since, for each standard, we immediately followed each reflection measurement by the corresponding transmission measurement. The time scale of the collection of reflected and transmitted data from either source for each standard was on the order of tens of seconds. Significant drift on a slower time scale has been documented for a virtually identical instrument [11].

Clearly, the simple drift correction applied here is far from ideal, and its potential advantage depends to a large degree on the details of the instrument and the experimental conditions. Therefore, it is essential to document its efficacy through experimental studies. A much more effective approach to the problem is to correct the data before acquisition with a closed-loop time base correction algorithm such as that discussed in [11].

IV. Measurements

The multiline TRL standards were constructed of coplanar waveguide on GaAs [13]. The five line standards included a 0.55 mm through line and four additional lines that were 2.135, 3.2, 6.565, and 19.695 mm longer. These were measured using on-wafer probes and a commercial sampling oscilloscope fitted with two 20 GHz TDR sampling heads. Two TDR and two TDT signals were measured for each standard. Unknowns were probed in the same fashion. After appropriate preprocessing, each waveform was subjected to a fast Fourier transform that was modified to account for the step-like nature of the waveform [14]. In some cases, we then applied a time-base drift correction. The results, considered as uncorrected scattering parameters, were used as input into the frequency domain multiline TRL calibration program. For comparison, the same standard and unknown structures were measured using a commercial FDNA.

Figure 2a displays the effective relative permittivity of the transmission lines, without applying drift correction. The results are comparable to the FDNA measurements but demonstrate an apparent broadband noise. In Fig. 2b, which is the result of drift correction, the magnitude of the apparently random noise is significantly reduced. The remaining systematic difference between the curves is consistent with a small residual offset error of about 0.07 ps (about 0.2 mm on the scale of Fig. 1). This difference is quite small for many practical applications, including the analysis of electronic packaging interconnections.

Figure 3a shows the measured relative phase constant and loss, without drift correction. On this scale, the TDNA and FDNA phase constants are quite similar. However, the TDNA loss data is of little use above 5 GHz. However, with drift correction (Fig. 3b), the loss data improves and is usable for many purposes up to 20 GHz.

As shown in Fig. 4, the drift correction also improves in the quality of characteristic impedance measurements. We made use of this data in subsequent network parameter determinations, presuming that it was equal to the initial reference impedance of the TRL-calibrated data.

Moving on to device measurements, Figure 5 shows the measured load impedance of a small resistor embedded at the end of a length of coplanar waveguide. Without drift correction (Fig. 5a), TDNA is clearly inadequate at all but the lowest frequencies. With drift correction (Fig. 5b), the TDNA measurements are dramatically improved.

V. Conclusions

The results show that the multiline TRL calibration is effective for TDNA but that time base drift correction is essential.

Our drift correction technique, while perhaps the best available based on external processing of stored waveforms, is essentially crude. More elegant approaches, implemented close to the time domain hardware, can make a more dramatic improvement [11]. We hope to soon demonstrate improved on-wafer TDNA using this internal correction scheme.

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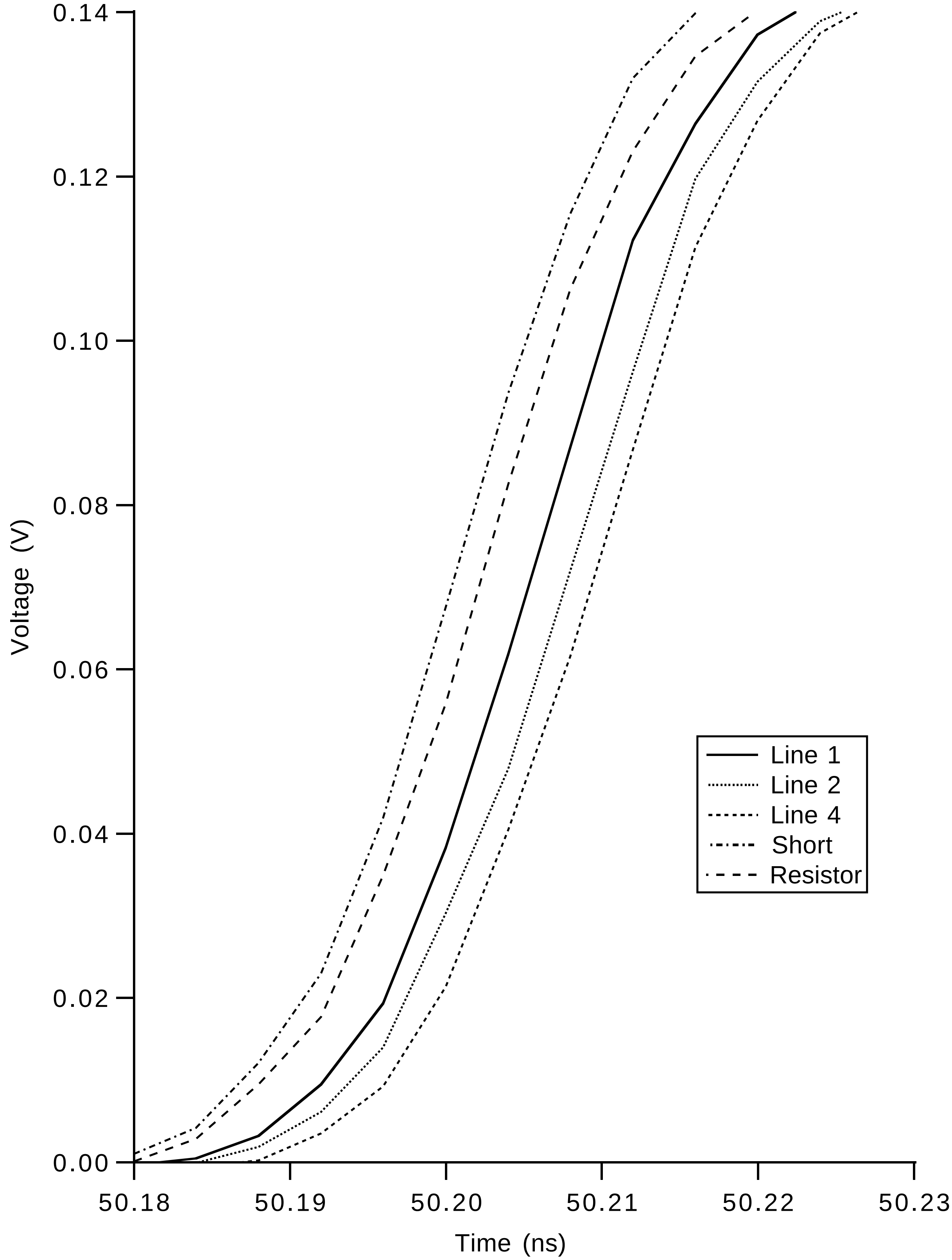

Figure 1. Incident Pulse Arrival Waveforms.

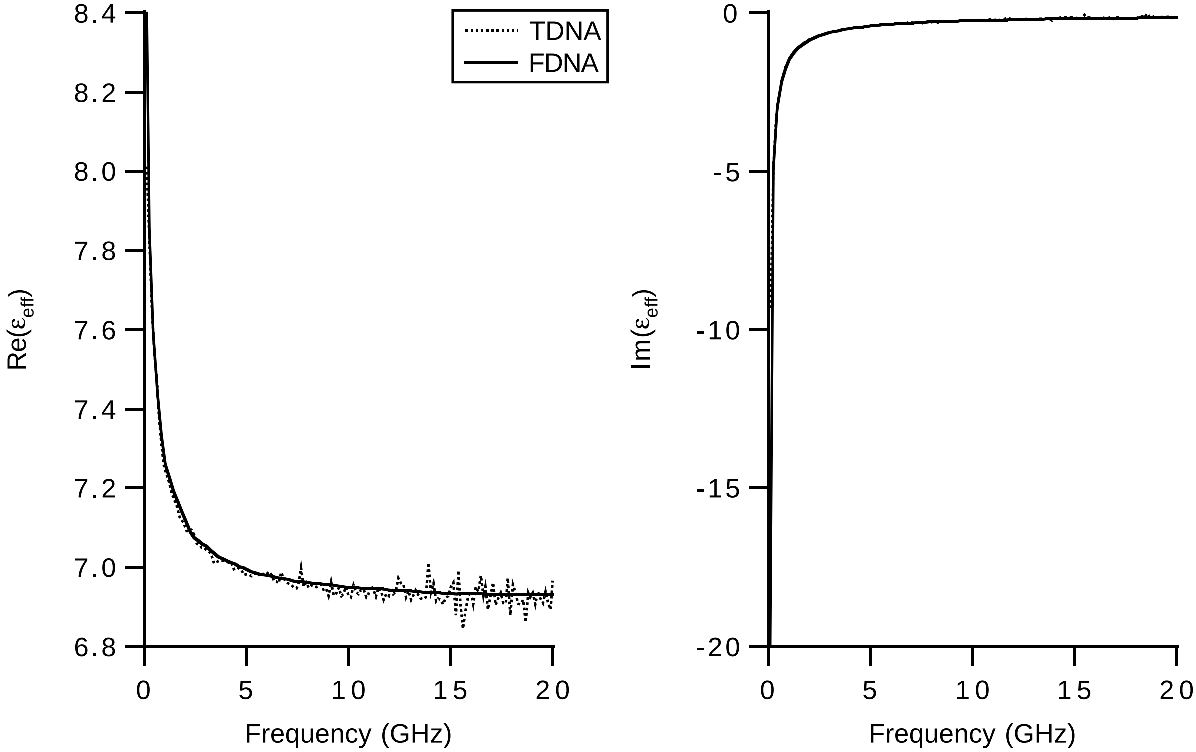

Figure 2a. Relative Effective Permittivity, No Drift Correction

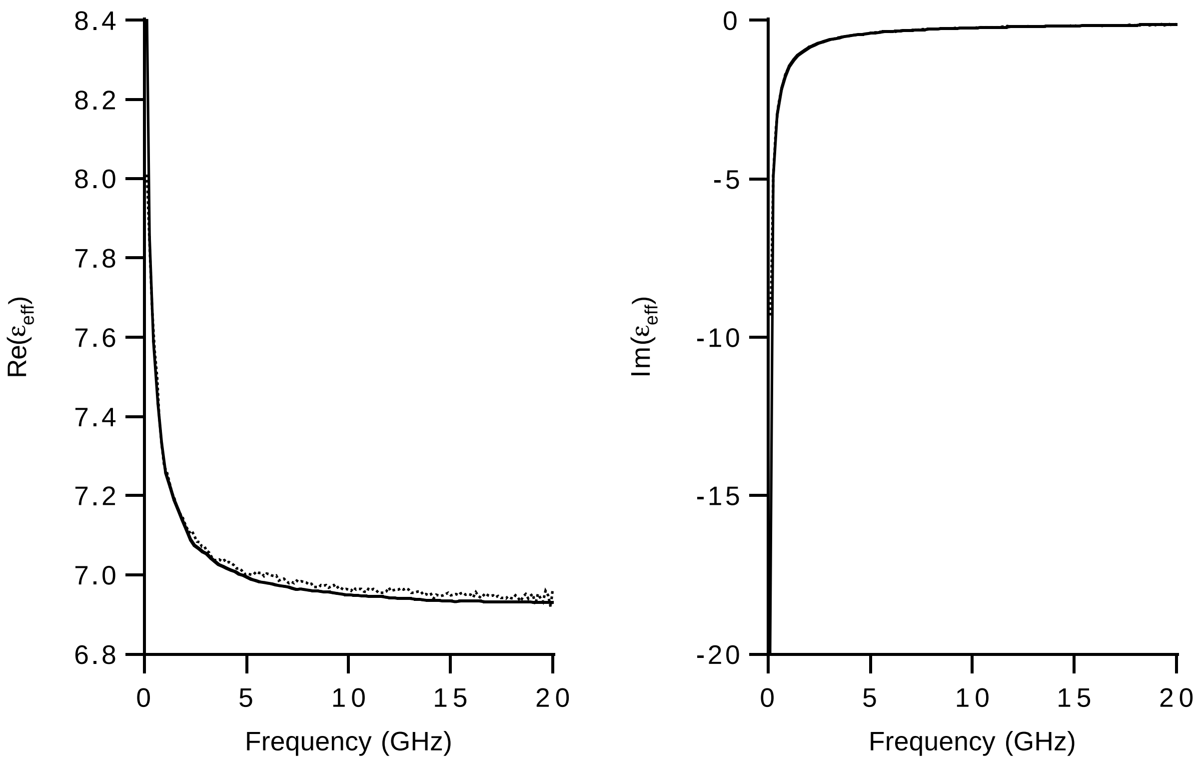

Figure 2b. Relative Effective Permittivity, Drift Correction

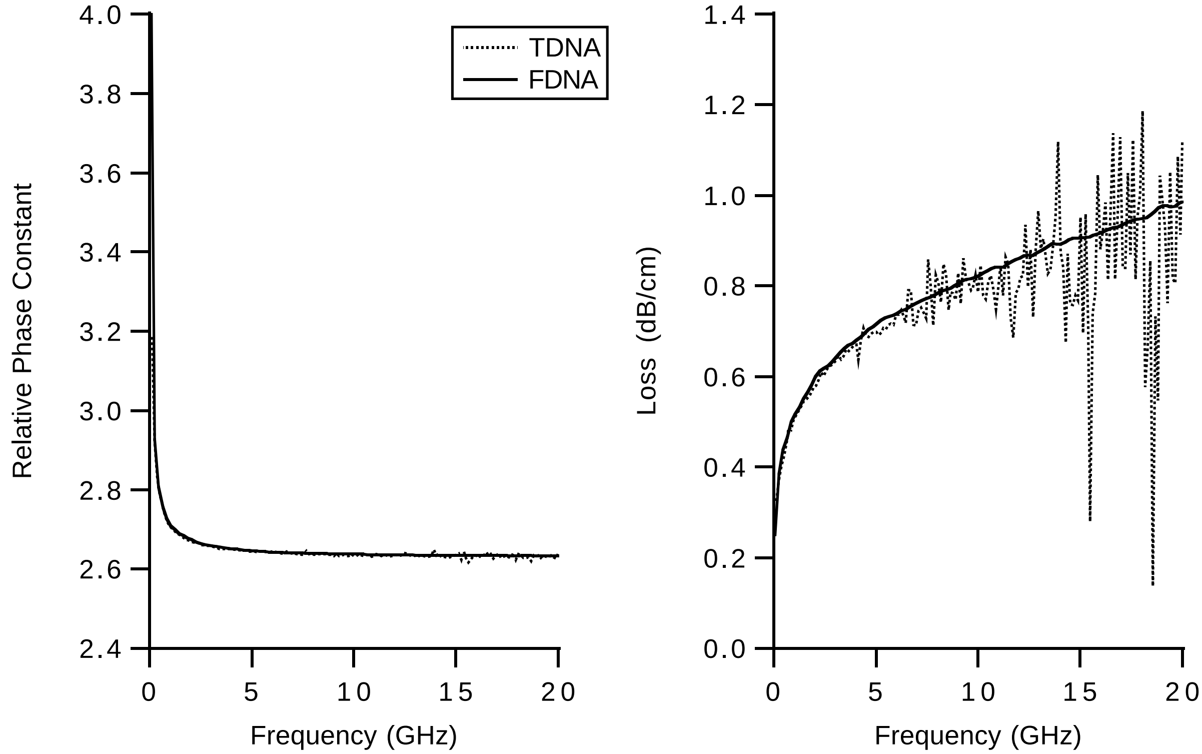

Figure 3a. Propagation Properties, No Drift Correction

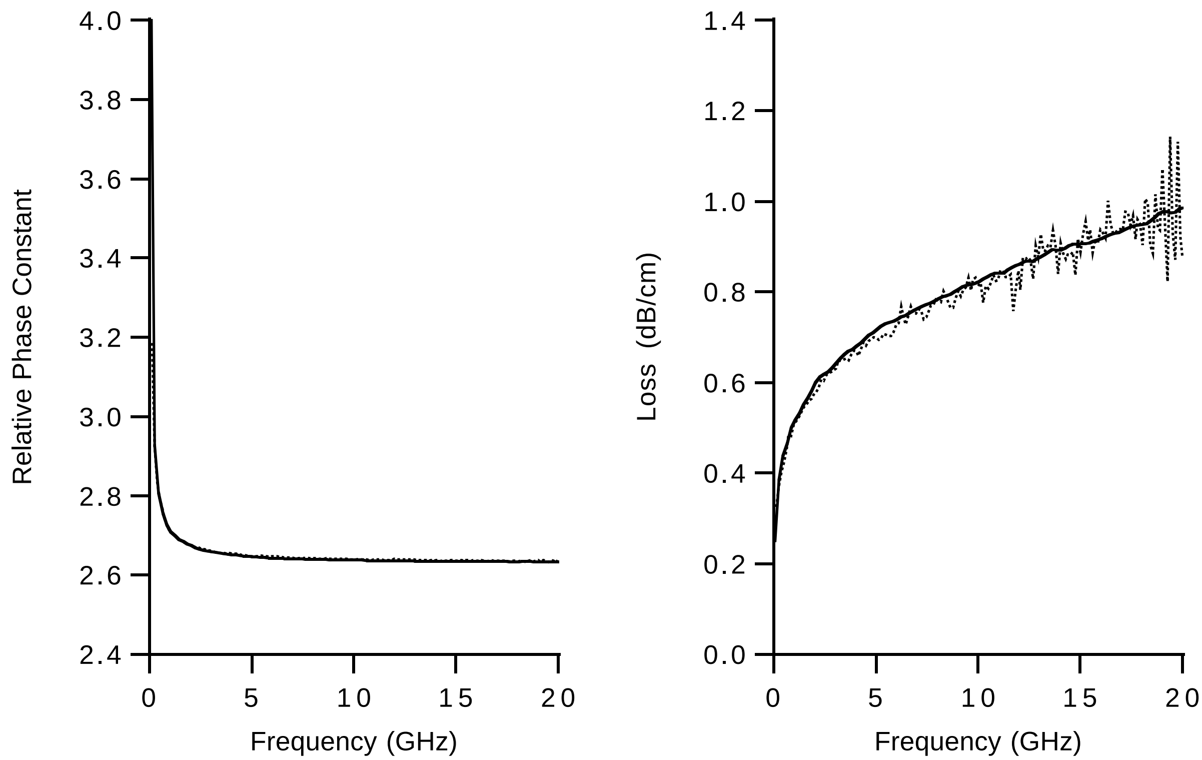

Figure 3b. Propagation Properties, Drift Correction

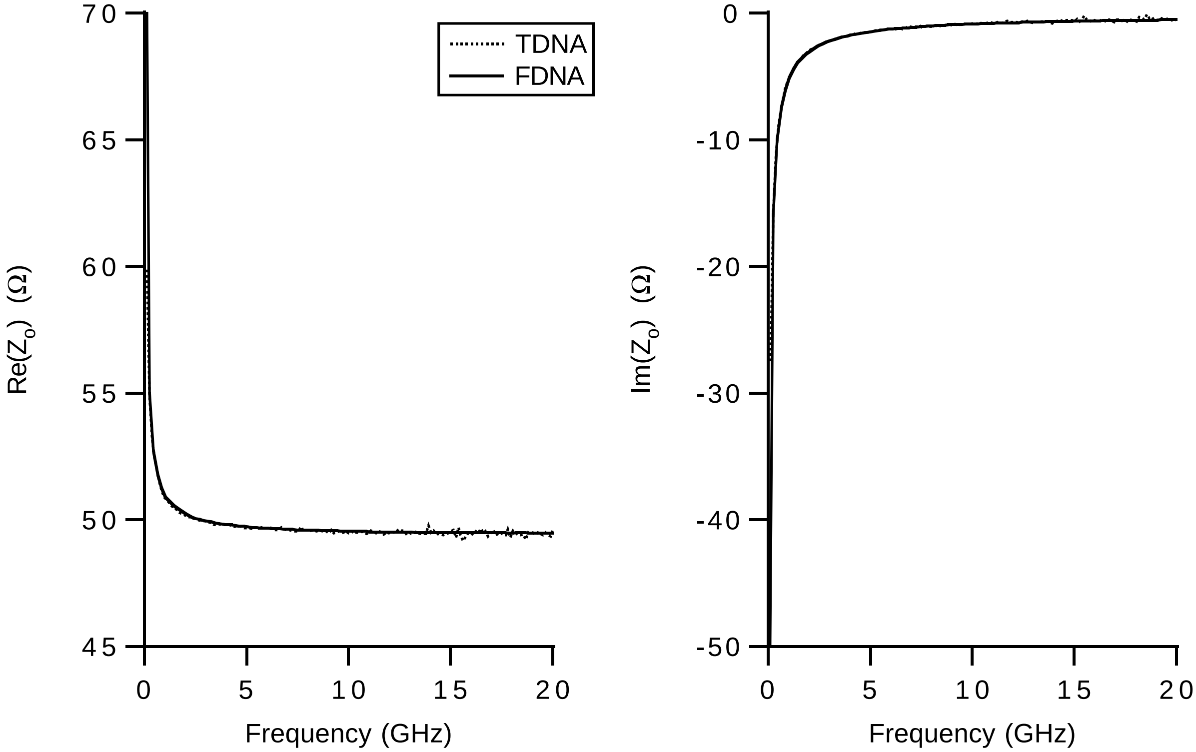

Figure 4a. Characteristic Impedance, No Drift Correction

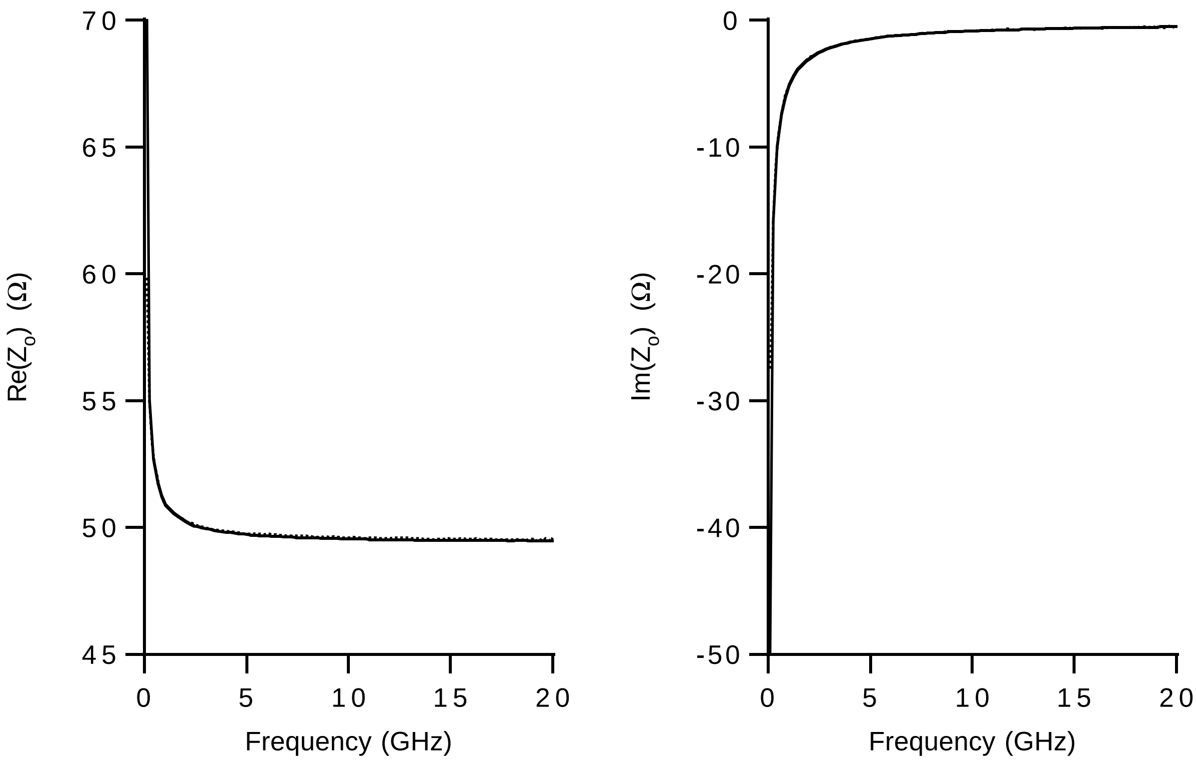

Figure 4b. Characteristic Impedance, Drift Correction

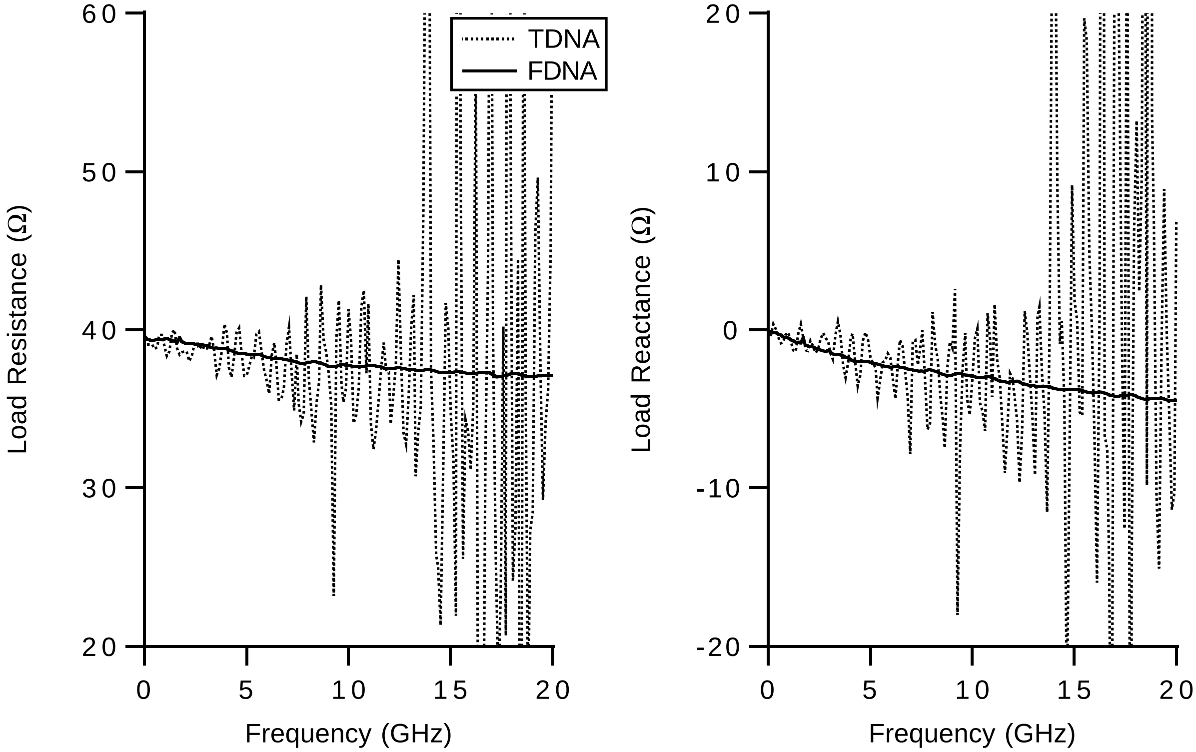

Figure 5a. Load Impedance, No Drift Correction

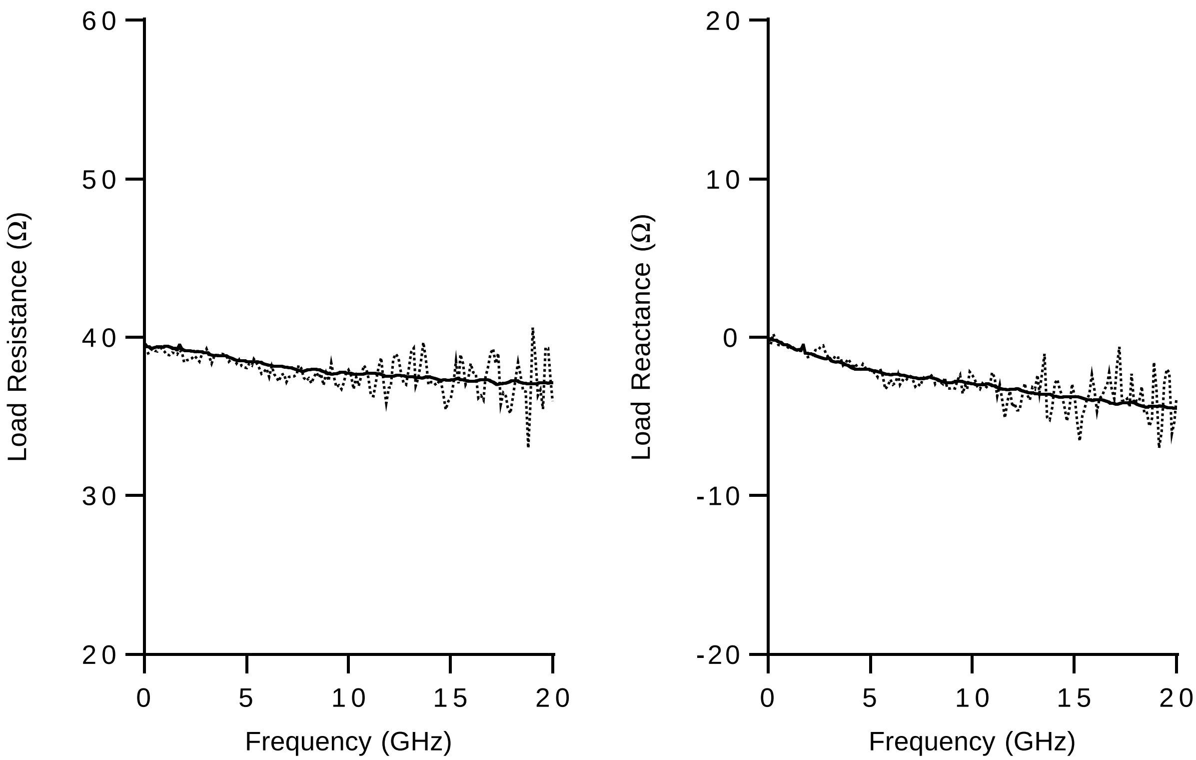

Figure 5b. Load Impedance, Drift Correction